Biocatalytic and Biomimetic Generation of Nitric Oxide *in situ* at Substrate/Blood Interfaces

Government Rights

This invention was made in the course of research partially supported by a grant from the National Institutes of Health, Grant Number GM 56991. The U.S. government has certain rights in the invention.

Relationship to Other Application(s)

This application is a continuation-in-part of U.S. Serial No. 60/262,014 filed on January 16, 2001, and claims the benefit thereof.

Background of the Invention

FIELD OF THE INVENTION

This invention relates generally to biocompatible materials, such as polymers or metals, and more particularly, to biocompatible materials having blood interface surfaces that are capable of biocatalytic or biomimetic generation of nitric oxide *in situ* when contacted with endogenous nitrite, nitrate, or nitrosothiols in blood.

DESCRIPTION OF THE RELATED ART

Although medical devices such as extracorporeal circuits and hemodialysis tubes are widely used in clinical settings, the polymers typically used to fabricate such devices (PVC, polyurethane, silicone rubber, *etc.*) are still subject to platelet aggregation and adhesion onto the surface of these materials. Thus, patients are often given anti-clotting agents (*i.e.*, heparin) in order to reduce thrombosis on the surface of these devices. Similarly, implanted devices made of stainless steel or other alloys, or even carbon, can cause thrombus formation when in direct contact with blood. There is, therefore, a need for materials that more closely simulate the antithrombogenic properties of the endothelial cells that line blood vessels in order to obviate the need to administer anticoagulants.

Nitric oxide (NO) is an important intracellular and intercellular messenger molecule that plays an important physiological role in anti-platelet aggregation and anti-platelet activation, vascular relaxation, neurotransmission, and immune response. It has been proposed that synthetic materials that release low levels of NO would, therefore, more closely simulate the natural activity of endothelial cells, and therefore, would have improved biocompatibility.

Several classes of NO-releasing materials are currently under investigation worldwide. These include NO donors (*i.e.*, diazeniumdiolates, nitrosothiols) that may be relatively complicated to synthesize and may, in some instances, require stringent storage conditions. Thus, there is a need for improved materials that are easier to fabricate and store.

Currently, NO generation is determined by water uptake (such as in the case of diazeniumdiolates) or the intensity of light (as with iron nitrosyls). However, blood already contains a host of species that are derived from, or are physiologically-generated *in vivo* that can be reduced to NO. These species include nitrites, nitrates, and a host of nitrosothiols (*e.g.*, nitrosoglutathione, nitroso albumin, *etc.*). This raises the possibility of recycling these species back to nitric oxide. There is, therefore, a need for materials that can reduce these species to nitric oxide locally at the substrate/blood interface.

It is an object of this invention to provide improved materials for biomedical applications that are capable of releasing NO from blood-contacting surfaces materials, so as to prevent platelet activation and adhesion onto these surfaces, thereby lowering thrombus formation and other complications associated with interactions between blood and foreign materials.

It is a further object of this invention to provide improved materials for biomedical applications that are relatively inexpensive to manufacture and that have improved biocompatibility.

It is still a further object of this invention to provide materials for biomedical applications that are capable of releasing NO from blood-contacting surfaces materials in response to nitrites, nitrates, and nitrosothiols in the blood.

Summary of the Invention

The foregoing and other objects are achieved by this invention, which provides a novel approach for enhancing the biocompatibility of materials of the type suitable for implantation in a human or animal body and/or for prolonged contact with the body or blood. In accordance with a broad aspect of the invention, materials have been developed to have a catalytic surface that is capable of generating, at the catalytic surface/blood interface, physiologically significant amounts of NO when in contact with blood. A catalytic agent, having nitrite reductase activity and/or nitrite reductase-like activity, or nitrosothiol reductase activity, is immobilized, adsorbed, adhered, or otherwise made available at a surface of the material.

In some embodiments, the catalytic agents are biocatalysts, such as enzymes, having nitrite reductase and/or nitrite reductase-like activity, or nitrosothiol reductase activity. Illustrative examples of the biocatalyst include nitrite reductases, nitrate reductases, enzymes having nitrosothiol reducing ability, and xanthine oxidase, or combinations thereof. Due to the ease of procuring xanthine oxidase commercially (*e.g.*, Sigma, St. Louis, MO), xanthine oxidase is a preferred embodiment. Other potentially useful immobilized biocatalysts include nitrite reductases and nitrate reductases from plants or bacteria.

In other embodiments, the catalytic agent is a biomimetic catalytic agent. As used herein the term "biomimetic catalytic agent" refers to a species possessing nitrite reductase-like activity, or the ability to reduce nitrosothiols which converts endogenous or exogenous nitrite/nitrate or nitrosothiols to NO when in contact with blood.

Illustratively, the biomimetic catalytic agent is a metal ion ligand complex wherein the metal ion is capable of reducing one or more of nitrite, nitrate, nitrosothiols, and other blood species to nitric oxide. In particularly preferred embodiments, the metal ion ligand complex is a Cu(II) complex. Neutral carrier type ligands that have high metal binding affinity, particularly for copper, are suitable for use in the practice of the invention. Further suitable neutral carrier type ligands include those having planar square-type geometry that provides a minimum amount of steric hindrance to the approach of the electron source (*e.g.*, ascorbate or NADH) to the center metal of the complex so that the copper ion can easily be reduced from Cu(II) to Cu(I). Examples include, without limitation, nitrogen or sulfur donating compounds, such as N_x-donor macrocyclic ligands (x=2, 4, 5, 6, 8) such as cyclen, cyclam and their derivatives, and crown ethers and S_x-donor macrocyle-type ligands (x=2, 4, 5, 6, 8).

In specific illustrative embodiments, the biomimetic catalyst is a Cu(II) metal ion ligand complex selected from the group consisting of dibenzo[e,k]-2,3,8,9-tetraphenyl-1,4,7,10-tetraaza-cyclododeca-1,3,7,9-tetraene; dibenzo[e,k]-2,3,8,9-tetramethyl-1,4,7,10-tetraaza-cyclododeca-1,3,7,9-tetraene; and dibenzo[e,k]-2,3,8,9-tetraethyl-1,4,7,10-tetraaza-cyclododeca-1,3,7,9,-tetraene.

As used herein, the term "material," when referring to the material that is provided with the catalytic surface, may be any material. In an embodiment, the material is of a type that is suitable for contact with the body and/or body fluids, particularly blood, of a living being, e.g., a material that is physiologically acceptable and non-toxic. In some

embodiments, the material should be suitable for long-term contact, or in-dwelling uses. Non-limitative examples of such materials include polymers, metals and alloys thereof, and carbon (graphite).

Many polymeric materials are suitable for the practice of the invention, and the following illustrative list of polymers that has been used for biomedical applications, is not intended to be limiting in any manner. Examples include synthetic polymers such as polyurethane, polydimethylsiloxane, ethylene vinyl acetate, nylons, polyacrylic, polymethyl methacrylate, polyamide, polycarbonate, polyester, polyethylene, polypropylene, polystyrene, poly(vinyl chloride) (PVC), polytetrafluoroethylene (PTFE), and cellulose acetate.

In an embodiment, the material includes a hydrophobic polymer substrate, such as poly(vinyl chloride), polyurethane, and silicone rubber, and a layer of a catalytic agent having nitrite reductase activity and/or nitrite reductase-like activity, or nitrosothiol reductase activity attached to a surface of the hydrophobic polymer substrate. The attachment may be by adsorption, covalent bonding, and the like. In an embodiment, the polymer substrate may include lipophilic salts of nitrite,nitrates, or nitrosothiols within its matrix to create a reservoir of nitrite, nitrate, or nitrosothiol that can continuously leak to the catalytic surface.

In embodiments where the "material" is a polymer, the NO-releasing polymer can be formed, cast, or otherwise shaped to form a monolithic device, such as an implantable device (e.g. a drug depot) or in-dwelling devices, (e.g. catheters, or extracorporeal tubing sets (non-limitative examples include kidney dialysis or open-heart surgery heart-lung machines)) and/or the like. The polymer may also be applied as a film on another substrate, such as, for example, a polymer substrate, or on another surface, such as, for example, the surface of a metal device.

Suitable metals include, but are not limited to, stainless steel, nickel, titanium, aluminum, copper, gold, silver, platinum and combinations thereof. The metal material may form medical devices. The following types of devices, provided with a catalytic agent in accordance with the principles of the invention, are meant to be illustrative, but not limiting, examples: arterial stents, guide wires, catheters, bone anchors and screws, protective platings, hip and joint implants, spine appliances, electrical leads, biosensors, and probes.

Further, the material may be a metal substrate. In an embodiment, the metal substrate may have a biomimetic catalytic agent covalently attached to its surface. As stated above, in an embodiment, the biomimetic catalytic agent is a metal ion ligand complex which is capable of reducing one or more of nitrite, nitrate, nitrosothiols, and other blood species to nitric oxide. In particularly preferred embodiments, the biomimetic catalytic agent is a Cu(II) metal ion ligand complex. Attachment of the metal ion ligand to the metal surface may be accomplished by any suitable means. One such technique involves silanizing the surface of the metal to provide reactive sites to bind the ligand.

In certain embodiments, an exogenous source of nitrites, nitrates, or nitrosothiols is provided in the polymer to form a reservoir of nitrite, nitrate, or nitrosothiol that can continuously leak to the catalytic surface of the material. In these embodiments, the exogenous source (a non-limitative example of which includes lipophilic salts of nitrites, nitrates, or nitrosothiols) is dispersed within the material. In some embodiments, the polymeric material containing the exogenous source of nitrite/nitrate or nitrosothiol is applied to a catalytic surface as a coating. Some non-limitative examples of the source of nitrites, nitrates, or nitrosothiols, include, without limitation, quaternary ammonium salts, such as tridodecylmethylammonium nitrite ($TDMA^+$ NO_2^-/NO_3^-); trimethyl phenyl ammonium; dimethyl dioctadecyl ammonium; *etc.* In addition to quaternary ammonium salts, quaternary phosphonium salts or quaternary arsonium salts may be used in the practice of embodiments of the invention.

Methods of making the invention include swelling a polymer, such as a poly(vinyl chloride) (PVC) or silicone, in the presence of an organic solvent containing an appropriate nitrite/nitrate salt to form a nitrite/nitrate salt-containing polymer. The nitrite/nitrate salt-containing polymer is then coated with a layer of immobilized enzyme, illustratively a nitrite reductase enzyme, such as xanthine oxidase. Many techniques are available for immobilizing enzymes. For example, see, Hasselberger, "Uses of Enzymes and Immobilized Enzymes, Nellson-Hall," Chicago (1978) or Guilbault, "Analytical Uses of Immobilized Enzymes," Marcel Dekker, New York (1984).

In another embodiment of the method, the biomimetic generation of NO may be achieved by immobilizing metal-ion ligand complexes, on the surface of the material, or by dispersing these ligands within the material, which may be a polymer. In some embodiments, additional lipophilic nitrite/nitrate salts, or nitrosothiols, are added to an

underlying polymer matrix material or provided as a coating on the material, or as an additional layer.

Brief Description of the Drawings

Comprehension of the invention is facilitated by reading the following detailed description, in conjunction with the annexed drawing, in which:

Fig. 1 is a schematic illustration of NO generation in solution via nitrite reductase activity from the catalytic surface of a polymer loaded with nitrite salt;

Fig. 2 is a graphical representation of the NO-release profile from nitrite ion-pair doped polymer films having immobilized XO on the surface in the presence of sheep blood;

Fig. 3 is a schematic representation of NO generation from a polymer matrix that has been loaded with a nitrate salt and a Cu(II) ligand complex in accordance with the invention;

Fig. 4 is a schematic representation of a material, in accordance with the invention, wherein a Cu(II) ligand complex is covalently tethered to the surface;

Fig. 5 is a graphical representation of the surface generation of NO from a Cu(II) ligand complex-containing polymer film in a bulk solution containing nitrite and ascorbate;

Fig. 6 shows three examples of illustrative metal ligand complexes; and

Fig. 7 is a graphical representation of NO generation from a nitrite ion pair/Cu(II) complex, specifically the complex designated L2 in Fig. 6.

Detailed Description

In one embodiment of the method for making an improved NO-releasing polymer, the desired polymer may be swelled in an organic solution containing the lipophilic nitrite/nitrate salt. In other embodiments, the salt can be added during the processing stage when the desired end product is molded or cast from the native polymer material. In still other embodiments, the surface of the polymer material that will be exposed to blood (non-limitative examples of which include the outside surface of a catheter, the inner surface of tubing of the type used in extracorporeal circuits, or the surface of metal stents) may be coated, either by dip-coating or by another method, with a biocatalyst (enzyme) or biomimetic catalyst capable of reducing nitrate, nitrite, or nitrosothiols to

NO. The biocatalysts or biomimetic catalysts can also be covalently tethered to the surface of the material.

Fig. 1 illustrates a specific embodiment of the material of the present invention. Mammalian xanthine oxidase (XO) is used as the surface catalyst for nitrite reduction to NO. In the presence of nicotinamide adenine dinucleotide (NADH), or other reducing equivalents in blood, the surface catalyst will generate NO as the nitrite ions leak from within the material into this surface layer via exchange for chloride and bicarbonate within the blood. Referring to Fig. 1, a polymer matrix 11 that has been loaded with a lipophilic nitrite/nitrate salt of tridodecylmethylammonium 12 ($R^+NO_2^-$) that provides a source of nitrite ions (NO_2^-). A coating 13 of xanthine oxidase (XO) is located at the surface of the polymer matrix 11.

Preliminary feasibility studies have been carried out to demonstrate the basic concept of this invention. Xanthine oxidase was used as a model enzyme for nitrite reductase activity. PVC polymer films were doped with $TDMA^+ NO_2^-$ and then coated with a layer of immobilized XO.

Illustratively, the PVC polymeric film, or membrane, was prepared by a cocktail solution casting method as described, for example, in Mathison et al., Anal. Chem., Vol. 71, pages 4614-4621 (1999) or any of the patents referenced herein. The cocktail solution was prepared by dissolving the appropriate amounts of membrane components (polymer, plasticizers and, in some cases, an ion-exchanger) into a solvent, illustratively tetrahydrofuran (THF). The membranes were cast in a mold to a final thickness of about 150 μm.

The polymer film was then coated with immobilized XO, prepared by crosslinking XO with bovine serum albumin (BSA) in the presence of glutaraldehyde. The cross-linked product forms a hydrogel that is dip-coated on the PVC polymer substrate.

An electrochemical sensor was used to probe the surface concentrations of NO generated when the coated film was placed into a buffered solution containing NADH at physiological pH. Significant levels of NO were generated at the surface of the film under these conditions. The generation of NO near the surface of the polymer film continued for several hours as the nitrite in the film was exchanged for anions in the buffer phase.

In this particular embodiment, the electrochemical NO sensor used was similar in style to a conventional Clark type oxygen sensor. A glass coated Platinum (Pt) wire

served as the anode and a Ag/AgCl wire (0.25 mm dia.) was used as the cathode. The internal filling solution was composed of 0.3 mM HCl and 30 mM NaCl, pH 3.5. An outer gas permeable membrane (Goretex, polytetrafluoroethylene with 50% porosity and 0.2. μm pore size) was placed between the internal filling solution and sample solution. Amperometric NO measurements were performed using an electrochemical analyzer.

Fig. 2 graphically illustrates that, when a similar film coated with XO was exposed to whole sheep blood, without the addition of any reducing equivalents in the form of NADH, measurable levels of NO were generated at the surface of the film as detected by the aforementioned electrochemical NO sensor. This data suggests that there is adequate endogenous reducing equivalent species in blood to serve as the source of electrons for the biocatalytic reaction at the surface of a polymer prepared in accordance with the present invention.

In another illustrative embodiment, biomimetic catalysts, such as Cu(II)-ligand complexes, for example, dibenzo[e,k]-2,3,8,9-tetraphenyl-1,4,7,10-tetraaza-cyclododeca-1,3,7,9-tetraene, were either incorporated in or tethered to a polymer or other material surface, such as a metal. Examples of this embodiment are shown in Figs. 3 and 4.

Fig. 3 is a schematic representation of a polymer matrix 31, illustratively PVC, that has been loaded with a lipophilic Cu(II) ligand complex 32 as well as a lipophilic nitrite/nitrate salt of tridodecylmethylammonium 33 ($N^+NO_2^-$) that provides a source of nitrite ions (NO_2^-) in the polymer. When the polymer 31 is exposed to an aqueous solution containing ascorbate (ASC) or ascorbic acid, the ascorbic acid reduces the Cu(II) in the ligand complex 32 to Cu(I). The Cu(I) in turn reduces nitrites in the film to NO.

Fig. 4 is a schematic representation of a material 40 that has a catalytic surface 41 created by tethering a Cu(II) ligand complex 42 to the surface. When the catalytic surface 41 is exposed to an aqueous solution, which may be blood, containing ascorbic acid, the ascorbic acid reduces Cu(II) in the ligand 42 to Cu(I). The Cu(I) returns to Cu(II), thereby converting nitrites and nitrosothiol (RSNO), for example, in the solution to NO.

Fig. 5 is a graphical representation of the surface generation of NO from a Cu(II) ligand complex-containing polymer film in a bulk solution containing nitrite and ascorbate. The data is plotted as NO concentration in parts per billion (ppb) as a function of time in seconds.

Three films having the following formulation were prepared in accordance with the method set forth above: 66.7 wt% PVC polymer (132 mg); 33.3 wt% plasticizer,

illustratively nitrophenyloctyl ether (NPOE; 66 mg), and Cu(II) ligand complex, CuL_xC1_2 (2 mg), L_x being one or more of ligands L1-L3 as shown on Fig. 6. The illustrative metal ligand complexes, specifically Cu(II) ligand complexes, shown in Fig. 6 are dibenzo[e,k]-2,3,8,9-tetramethyl-1,4,7,10-tetraaza-cyclododeca-1,3,7,9-tetraene, labeled L1; dibenzo[e,k]-2,3,8,9,-tetraethyl-1,4,7,10-tetraaza-cyclododeca-1,3,7,9-tetraene, labeled L2; and dibenzo[e,k]-2,3,8,9-tetraphenyl-1,4,7,10-tetraaza-cyclodeca-1,3,7,9-tetraene, labeled L3.

Although these complexes are shown as chloride salts, it is to be understood that other counterions are appropriate. Other metal ions were evaluated for activity, *i.e.*, ability to mediate the reduction of nitrite to NO by ascorbate, including Co(II), Ni(II), Zn(II) Mn(II), A1(II), and Fe(III). Of these ions, Fe(III) yielded a detectable level of NO, but this was far less than that observed with Cu(II) under identical conditions. Other metals, such as V(III), Cr(III), and Ti(III) have also been suggested as being capable of reducing nitrite to NO. However, unlike Cu(II) or Fe(III), these metals are not present in appreciable levels *in vivo*, either within physiological fluids or within specialized cellular vesicles. Therefore, Cu(II) is presently the preferred metal ion for the practice of the invention.

Referring back to Fig. 5, the traces represent ligands L1-L3, respectively. In this particular experiment, the bulk solution was deoxygenated phosphate buffered saline (PBS) having a pH of 7.4. At time t=0, 1 mM nitrite and 1nM ascorbate were added to the PBS solution and NO generation was measured with a chemiluminescense detector. The results demonstrate that films in accordance with the present invention are capable of NO generation at the interface when the nitrites and ascorbates are in the bulk solution, such as would occur when the films were placed in contact with blood in an *in vivo* situation.

Fig. 7 is a graphical representation of NO generation from a nitrite ion pair/Cu(II) complex, specifically the complex designated L2 in Fig. 6, doped into a polymer film. The data is plotted as NO concentration in parts per billion (ppb) as a function of time in minutes following the introduction of 1mM ascorbate into a deoxygenated PBS solution having pH 7.4.

The polymeric film compositions used in this experiment are as follows:

Film 1:

66 mg PVC; 132 mg NPOE; 4 mg Cu(II) complex; and 20 mg ion pair or $TDMA^+NO_2^-$

Film 2:

100 mg PVC; 100 mg NPOE; 4 mg Cu(II) complex; and 20 mg ion pair

Film 3:

132 mg PVC; 66 mg NPOE; 4 mg Cu(II) complex; and 20 mg ion pair

These results show generation of NO by the polymer film that is particularly good for the highly plasticized embodiments.

The major advantage of this technology over the previous methods for generating NO locally at the surface of polymers or other materials is the potential simplicity of simply dip-coating the material with a biocatalytic or biomimetic catalytic layer. The catalytic layer may have a single catalyst or a mixture of reductase activities. It may be a biological protein (enzyme) or a metal ion-ligand complex that mimics the enzyme function. Even in those embodiments where added $TDMA^+$ NO_2^-/NO_3^- or some other nitrite/nitrate salt, or a nitrosothiol, such as nitroso cysteine, is required or desired, within the material, the stability of such species is likely to far exceed the stability of diazeniumdiolates and other NO donors used to date.

In a clinical situation, it should be noted that, even if the amount of reducing equivalent species in the blood were to vary from test subject to test subject, it is possible to add reducing equivalents of an alternate electron donor to the blood, illustratively in the form of ascorbic acid, by administering low doses of Vitamin C to the patient. This may aid in ensuring the presence of adequate levels of reducing equivalents.

Although the invention has been described in terms of specific embodiments and applications, persons skilled in the art can, in light of this teaching, generate additional embodiments without exceeding the scope or departing from the spirit of the invention described herein. Accordingly, it is to be understood that the drawing and description in this disclosure are proffered to facilitate comprehension of the invention, and should not be construed to limit the scope thereof.